

TWO FREQUENCY OPERATION OF THE ARGONNE ECR ION SOURCE

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Abstract

Performance of the Argonne ECR ion source has been improved through the use of two frequency heating – the primary frequency of 14 GHz from a klystron and the second frequency from a traveling wave tube amplifier (TWTA) with a tunable range of 11.0 – 13.0 GHz. Source output as well as stability have been improved with a shift to higher charge states observed. A larger separation between the two operating frequencies has demonstrated improved beam production as well as greater stability. The addition of 60 watts at 10.85 GHz produced a 69% increase in O^{7+} beam production, whereas a similar increase to the 14 GHz RF power alone, without the addition of a second frequency, produced only a 20% increase in beam production. Use of a second frequency has increased the intensity of the medium charge states by 50-100% ($^{56}Fe^{13+}$: $10.6 \rightarrow 17.4 \mu A$; $^{86}Kr^{15+}$: $65 \rightarrow 120 \mu A$) and the higher charge states a factor of 2 to 5 ($^{56}Fe^{17+}$: $1.15 \rightarrow 6.40 \mu A$; $^{238}U^{37+}$: $2.0 \rightarrow 3.0 \mu A$). Operational modes and results will be presented.

INTRODUCTION

The demand for high charge-state high-intensity beams has motivated the return to two-frequency heating. A new program for the production of super-heavy nuclei has begun which requires intense beams of rare isotopes. In order to limit the consumption of the expensive isotopic material required to produce these beams, an increase in source efficiency and beam production is required. Two-frequency heating is one component in a program to accomplish these goals and further optimize source performance.

Two-frequency heating improves beam production by providing a second resonance surface for electron heating [1]. ECR 2 originally took advantage of this condition through operation at 10.5 and 14.0 GHz [2] until the 10.5 GHz magnetron that provided the second frequency failed and no replacement magnetron was available. A traveling wave tube amplifier (TWTA) with a tunable range of 11.0 – 13.0 GHz was recently purchased to replace the failed magnetron. The tunable aspect of the TWTA allows the transmitter to operate as either the primary or secondary frequency for either of the two ECR ion sources at the ATLAS facility.

SOURCE CONFIGURATION

All of the tests with two-frequency heating were performed on ECR 2 [3]. The two frequencies are coupled into the plasma chamber through the injection plug. The 14 GHz power is provided by a 2.5 kW klystron and is launched from a WR62 waveguide, while the RF power provided by the 0.5 kW TWTA is launched from a WR90 waveguide set at 150° to the WR62 guide. The power output at the flange of the TWTA varies $\pm 3.0\%$ across its operating range of 11.0 – 13.0 GHz. When coupled to the waveguide, this variation increases to $\pm 10\%$. The reflected power for the TWTA was measured using a dummy load and optimum operating frequencies were found based upon coupling into the waveguide configuration. Care was also taken during source operation to operate the TWTA at frequencies that were strongly coupled into the plasma. The amount of 14 GHz power reflected back to the TWTA was measured and found to be < 5 W. No external circulators are used on either transmitter.

EFFECT OF FREQUENCY GAP AND RF POWER

The first test with ^{16}O was intended to characterize the source performance with the TWTA. The beam output was observed as a function of overall RF power, frequency gap, and coil configuration. The source output and stability was found to improve as the separation between the primary and secondary frequencies was increased. A shift in the TWTA frequency from 11.67 to 10.85 GHz produced an 11.5% increase in $^{16}\text{O}^{7+}$ beam production as well as improved stability. It was also noted that the coil configuration did not change significantly between single and dual frequency operation.

The effect of the frequency gap on beam output was further pursued with ^{20}Ne . The TWTA frequency was varied between 12.21 and 10.84 GHz with the $^{20}\text{Ne}^{9+}$ output increasing by 47.7%. The data presented in figure 1 was collected at operating frequencies that produced the best coupling into the source. The output power of the TWTA was kept at 100 W and all other source parameters were adjusted at each frequency to maximize beam production. In addition to the increase in the 9+ intensity, the intensities of the low to mid charge states decreased while the intensities of the high charge states increased as a function of increasing frequency separation. This is a possible indication of a higher electron temperature or density. The extraction drain current increased from 1.31 to 1.82 mA further indicating the higher overall beam output and a higher plasma density.

Further testing demonstrated that the observed increases in beam output were not a result of the higher overall RF power being launched into the source but rather were due to the two distinct ECR zones established by the two frequencies. This is detailed in figure 2, which shows the performance of $^{16}\text{O}^{7+}$ at various TWTA frequencies and power levels. The source was optimized on O^{7+} with 427 W at 14 GHz. The TWTA was then energized and its power output set to 60 W at 11.06 GHz, resulting in a 46% increase in beam current. The frequency of the TWTA was then shifted from 11.06 to 10.85 GHz with a further improvement to 69%. De-energizing the TWTA reduced the beam current to 15 μA , well below the original output level, and shifted the peak of the charge state distribution from 6+ to 5+. Raising the voltage of the biased disk increased the beam current to 32 μA , but no other source parameters affected the beam intensity.

The source was then optimized with an additional 60 W of 14 GHz RF power so that the total RF power was the same as during two-frequency operation. The $^{16}\text{O}^{7+}$ output increased to 38.5 μA and the CSD peak shifted back to 6+, but the 66 μA achieved with combined frequency operation could not be duplicated, even with the addition of another 300 W of 14 GHz RF power.

The inability to duplicate in single frequency mode the source performance achieved in two-frequency mode is further highlighted in figure 1. The square symbol at 14 GHz corresponds to the source output with 14 GHz heating alone. The round symbol above it corresponds to 14 GHz operation but with the addition of 100 W to match the overall RF input power utilized during two-frequency operation. If the total RF power were the defining factor for the source performance, it would be expected that the source output during single and two-frequency operation would be identical at the same overall RF power level and the same source operating conditions. Instead it is observed that the source output increases as the frequency separation is increased, indicating the importance of the two independent ECR zones. The importance of the frequency separation is a possible explanation for the initial results using two-frequency heating [4] where the frequency separation was < 1.0 GHz.

EFFECT OF AXIAL MAGNETIC FIELD

The effect of the axial magnetic field on source output was tested using a ^{20}Ne beam. The source was tuned for $^{20}\text{Ne}^{9+}$ achieving an output of 1.65 μA with 550 W at 14 GHz. The TWTA was then energized to 200 W at 10.87 GHz, raising the $^{20}\text{Ne}^{9+}$ current to 3.2 μA . Increasing the axial

magnetic field raised the beam output to 11.0 μA . De-energizing the TWTA at the final settings produced a 4.0 μA beam – a 63.6% decrease in intensity.

The increase in the axial field resulted in a 11.7% increase in B_{min} and shortened the 10.87 GHz ECR zone from 7.0 to 4.3 cm. The 14 GHz zone was shortened as well from 11.8 to 10.2 cm. This would indicate that a smaller ECR zone for the lower frequency is more effective. Similar behavior was observed at the LBL AECR-U [5]. In this situation the RF power density increases producing an enhancement in the high charge state ions.

GENERAL RESULTS

A summary of the overall results with two-frequency heating is presented in figure 3. Results for ^{16}O , ^{20}Ne , ^{56}Fe , ^{86}Kr , and ^{238}U are shown. In general, the mid-charge state intensities increased by 50 - 100%, while the high charge states increased by a factor of 2 to 5. This corresponds with the data collected in 1998 during two-frequency operation [6] with oxygen and neon. This is also in good agreement with data collected by the LBL group with bismuth and uranium [7].

As part of the super-heavy research program, an iron beam has been developed using the MIVOC method [8]. Iron beams have been produced previously using a high temperature oven, but the ferrocene allows a higher beam current and efficiency to be achieved. The gain in efficiency realized with the use of the ferrocene has been further extended with the use of two-frequency heating. The use of the second frequency shifted the peak of the CSD from 13+ to 15+ with a factor of 3 increase in the 15+ beam current. In addition, the $^{56}\text{Fe}^{15+}$ efficiency improved from 0.19% to 0.47%. The MIVOC configuration is not yet optimized, with results from other labs showing larger beam currents as well as improved efficiencies [9,10,11].

The goal of the ^{86}Kr test was to produce 15 μA of $^{86}\text{Kr}^{14+}$, the intensity needed for the driver linac of the proposed next generation radioactive isotope accelerator (RIA). This goal was achieved with the production of 210 μA of $^{86}\text{Kr}^{14+}$ from the ion source with 974 W of 14 GHz RF power and 400 W from the TWTA at 10.81 GHz. The source extraction voltage was 14.0 kV with oxygen as the mixing gas. The krypton sample was 99.5% enriched in mass 86.

The sputter method was used to produce a beam of ^{238}U from a depleted metal sample. The sample was introduced radially and biased to -4.0 kV. Two separate tunes were performed using this method. The first was for maximum production of 28+ with 21.0 μA being achieved and this charge state being the peak of the CSD. The second tune was for maximum production of 37+ with the peak of the CSD shifting to 34+ and an intensity for $^{238}\text{U}^{37+}$ of 3.0 μA . Previous results with this technique produced a peak charge state of 31+ with an intensity of 6.0 μA .

This work supported by US D.O.E. Nuclear Physics Division under contract W-31-109-ENG-38.

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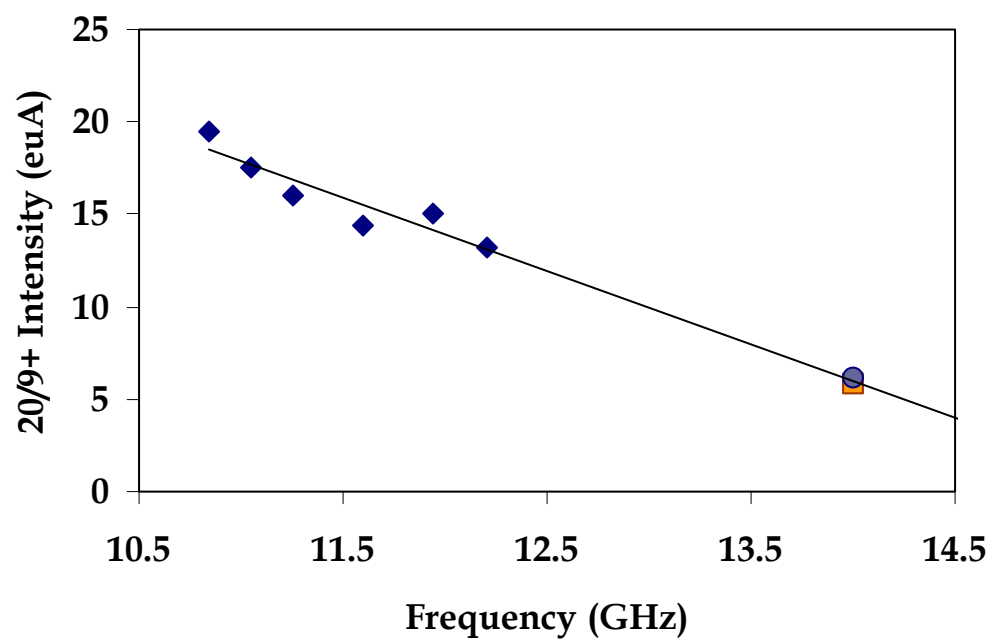


Figure 1: $^{20}\text{Ne}^{9+}$ output as a function of TWTA frequency operating at 100 W. The 14 GHz was held at 821 W. All other source parameters were tuned at each TWTA frequency to maximize beam production. The square symbol at 14.0 GHz represents source output with 14 GHz operation alone. The round symbol at 14 GHz represents the addition of 100 w at 14 GHz (for a total of 931 W) to compensate for the lack of TWTA RF power.

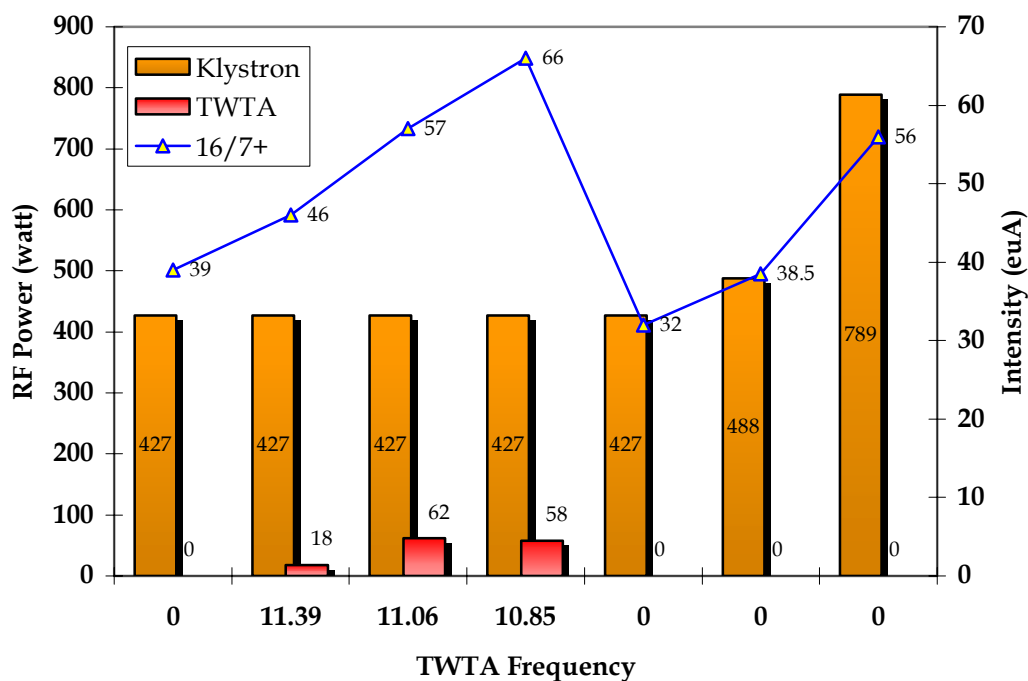


Figure 2: $^{16}\text{O}^{7+}$ performance as a function of RF power and frequency from the 14 GHz klystron and the tunable TWTA.

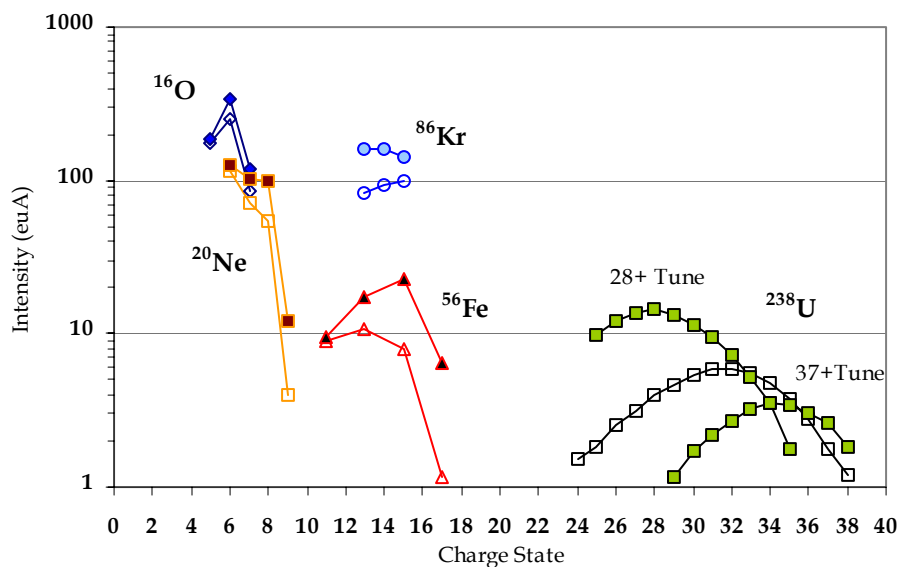


Figure 3: Increase in beam intensity of various ion species due to two-frequency heating. Filled symbols are with two-frequency heating. Source extraction voltage was 14.0 kV. Helium support gas was used with the Neon. Oxygen support gas was used with the Iron, Krypton, and Uranium beams. No support gas was used for the Oxygen.